The Causes and Impacts of Three Major Nuclear Accidents

Duanman XIONG[1],Guoyu CHEN[1],Yuxin FANG[1],Jingxu WU[2],Junwen WU[3],Jiaqi ZHANG[4]&Haoqin YANG[5]

1. School of Management, Lanzhou University, Lanzhou 730000, China
2. Key Laboratory of New Energy Materials Research, Xinjiang Institute of Engineering, Urumqi 830023,China
3.School of Water Resources and Hydropower Engineering, Gansu Agricultural University, Lanzhou 730070, China
4. Lanzhou No. 63 Middle School,Lanzhou 730000, China
5. Faculty of Arts, Cairo University, Giza 12613,Egypt

Abstract

This paper critically reviews the root causes and impacts of three significant accidents at large civilian nuclear power plants: the Three Mile Island accident in 1979, the Chernobyl accident in 1986, and the Fukushima Daiichi accident in 2011. The analysis encompasses health effects, evacuation measures in contaminated areas, cost estimates, and the repercussions on energy policies and nuclear safety initiatives across different countries. The study concludes that primary objectives for reactor safety work must prioritize preventing accidents from progressing into severe core damage, even when triggered by extremely improbable events, while also acknowledging the possibility of such accidents occurring. Additionally, efforts should focus on limiting releases of radioactive nuclides, such as cesium, to minimize large-scale and long-lasting ground contamination to less than approximately 100 TBq. The paper underscores the crucial role of maintaining high global standards of safety management and safety culture to achieve these objectives. It highlights that all three accidents discussed herein stemmed from systemic deficiencies indicative of inadequate safety management and culture within both the nuclear industry and governmental authorities.

Introduction

Ensuring the secure operation of nuclear power plants is paramount, necessitating strict adherence to safety measures and principles established at national, regional, and international levels. Ignoring or neglecting these safety protocols by nuclear plant operators can lead to nuclear accidents with severe repercussions for the environment, human health, and public perception[1]. Consequently, it is imperative for governments and nuclear power plant owners to conduct periodic assessments of nuclear power plant operations.

These assessments serve to ascertain whether an adequate level of safety has been achieved, ensuring compliance with safety objectives and criteria outlined by plant designers, operating organizations, and regulatory bodies. Safety assessments should be conducted systematically throughout the lifespan of nuclear power plants, with the primary goal of identifying radiation risks to workers, the public, and the environment during normal plant operations[2-4].

The overarching objective of safety assessment is to evaluate whether sufficient measures have been implemented by governments and nuclear power plant operators to manage radiation risks to an acceptable level, encompassing both the prevention of abnormal events and the mitigation of their consequences[5-6].

Table 1 .Since 1959, ten major nuclear accidents have been recorded by five countries

No.	Nuclear Accident	Country	Year
1	The Kyshtym disaster	Soviet Union	1957
2	The Windscale fire	United Kingdom	1957
3	The Three Mile Island accident	United States	1979
4	The Chernobyl disaster	Ukraine	1986
5	The Fukushima Daiichi nuclear disaster	Japan	2011

The fission process serves as both a power source in nuclear energy production and a significant source of risk in the operation of nuclear power plants. During fission, uranium and plutonium nuclei split, generating numerous radioactive fission products. In the event of a serious accident, these radioactive byproducts have the potential to escape into the environment and disperse widely.

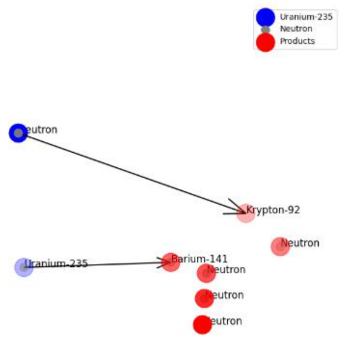

Figure 1 Schematic diagram of fission reaction

During normal operation and some events and interferences considered in nuclear power plant design, these radioactive nuclides are prevented from escaping into the environment through several physical barriers. These are usually zirconium alloy tubes, in which uranium oxide fuel particles are sealed to form the steel pressure boundary of the reactor core, the coolant system of the reactor core, and the reactor safety shell. They are usually solid concrete structures that surround the main components of the reactor. Various safety systems, such as emergency cooling systems, are also designed to protect the integrity of these barriers in case of highly unlikely events. Therefore, preventing the release of radioactive materials into the environment is based on the so-called principle of defense in depth.However, as experience has shown, it cannot be completely ruled out that certain events occur that challenge the integrity of obstacles, go beyond their design scope (their design basis), and result in one or more obstacles failing. If all these methods fail, it is possible to release and diffuse a large amount of radioactive material into the environment. The main mechanisms that may lead to barrier failure are the loss of reactivity control (control of the fission process) and the cooling loss of the reactor core.The loss of reactivity control is due to the presence of sufficient fission material in the reactor core to operate at full power for one year or longer, which may result in an abnormal increase in power generation (power offset), energy release, and related forces far exceeding the design basis of the barrier, leading to barrier failure. To prevent such power offset, a highly reliable reactive control system is essential. In addition, most power reactor cores are designed for inherent stability and typically have a negative power response coefficient, which means that if power begins to increase, the inherent physical mechanisms in the core will reduce the fission rate.Even if the fission process stops, the cooling loss of the reactor core will continue to generate heat due to the energy released from the radioactive decay of fission products. In a typical water-cooled power generation reactor, the electrical output is 1000 MW, and the core generates approximately 3000 MW of thermal power during normal operation. In the first few seconds after shutting down the fission chain

reaction in the power reactor core, the residual heat generated by the decay of fission products is equivalent to about 7% of full power, or about 200 megawatts in a 3000 megawatt core. After 1 hour, the residual decay heat is equivalent to about 2% of full power or about 60 MW, and after 36 hours it is equivalent to about 15 MW.If the cooling water supply to the core is lost shortly after the fission process stops, this residual energy will cause the core to overheat, decompose, and eventually begin to melt, typically on a time scale of up to a few hours. Even if the supply of cooling water is lost, the zirconium cladding fuel in the core is usually surrounded by water vapor. Once the zirconium fuel cladding reaches approximately 1200 ° C, the heating and melting process will accelerate, and a rapid geothermal reaction will begin:

$$Zn + H_2O \rightarrow ZrO + H_2$$

In this chemical reaction mode, in addition to heat, a large amount of hydrogen gas is also produced. If it leaks into the reactor and its surrounding buildings with an oxygen-containing atmosphere, there is a possibility of destructive explosion or even detonation.

The main focus in terms of socio-economic impact is on the mechanisms by which fission products may cause serious core damage, which can also provide energy for the diffusion of fission products from damaged cores to the environment. If the remaining barrier to prevent radioactive release also fails, this situation will occur. Of particular concern is the release of fission products, which can cause large-scale land pollution and have significant impacts on the medium to long term socio-economic development. This fission product includes isotopes of iodine and cesium. These substances evaporate within the temperature range typically reached by the overheated core, and then form aerosols of various chemical components. Radioactive inert gases are of more short-term concern as they may cause high doses of harm to personnel on site and near factories. However, they usually quickly disperse in the atmosphere with little significant long-term socio-economic impact. In fact, the release of rare gases is equivalent to the release of toxic gases such as chlorine that may occur in traditional industrial accidents.Table 2 lists the typical radioactive content of some of the radioactive nuclides that are of primary concern in severe reactor accidents in the contemporary 3000 MW reactor core.

Table 2 . Typical activity content of a contemporary 3000 MW boiling water reactor (BWR) core (limited to some isotopes of main concern)

Isotope	Activity content in TBq (1012 Bq)	Half-life
Xenon-133 (Xe-133)	6 000 000	5.28 days
Iodine-131 (I-131)	2 900 000	8.04 days
Iodine-133 (I-133)	6 100 000	0.88 days
Cesium-134 (Cs-134)	310 000	2.06 years
Cesium-137 (Cs-137)	320 000	30.1 years
Strontium-90 (Sr-90)	250 000	28.5 years

Since the 1950s, a series of theoretical studies has been conducted to identify and assess the potential consequences of severe reactor accidents, which could result in the release of a significant portion of the core's fission products[7-8]. Initially, much of this research focused on evaluating the potential health effects of radiation exposure on populations residing at varying distances from nuclear power plants, examining both early and late mortality. However, these studies also considered the ground pollution resulting from various accident scenarios.

In Sweden, data from the 1957 Atomic Energy Commission report played a pivotal role in the evaluation of a proposal to construct a large nuclear reactor for regional heating and electricity production within Stockholm[9]. Ultimately, the proposal was rejected based on risk assessments stemming from this data. Furthermore, the Swedish Institute for Radiation Protection[10] utilized

findings from the 1975 Rasmussen study in a report completed in 1979. This report served as a foundation for enhancing Sweden's nuclear emergency plans.

The report emphasized that in the event of a serious accident involving the release of a substantial quantity of fission products, coupled with adverse weather conditions, the need for large-scale evacuations might arise. It highlighted the critical importance of controlling the release of long-lived fission products such as Cs-137 to below 0.1% of the 1800 MW reactor core content, approximately equivalent to 200 TBq. Adherence to this threshold could help avert widespread evacuations and the subsequent imposition of restrictions on food production land.

Around 1990, the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (OECD/NEA) initiated a collaboration to develop an international event rating scale. This scale aimed to consistently rate nuclear and radioactive events, facilitating the communication of their safety significance to the public, media, and technical community. This effort resulted in the creation of the International Nuclear and Radiological Event Scale (INES)[11]. The scale categorizes events into seven levels, with levels 4-7 classified as "accidents" and levels 1-3 as "events". Events with no safety significance are labeled as "below scale/level 0".

The impact of events is evaluated across three key domains: their effects on people and the environment, their ramifications for radiation barriers and facility control, and their implications for defense in depth. The highest level, level 7 is defined as an event causing environmental release with a radiation level equivalent to tens of thousands of terabecquerels of I-131 released into the atmosphere. At level 6, the release of I-131 ranges from thousands to tens of thousands of megabecquerels. It's important to note that the release of Cs-137 must be multiplied by a factor of 40 to be considered radiologically equivalent to I-131.

Figure 2 illustrates the nuclear facility events and their corresponding INES ratings. As of the end of 2011, encompassing approximately 13,000 reactor years of operation, three severe accidents occurred at major nuclear power plants: the Three Mile Island incident in 1979, the Chernobyl disaster in 1986, and the Fukushima Daiichi nuclear power plant accident in 2011. This paper will review these three accidents, while other events with significant radioactive consequences listed in figure 2 will not be addressed.

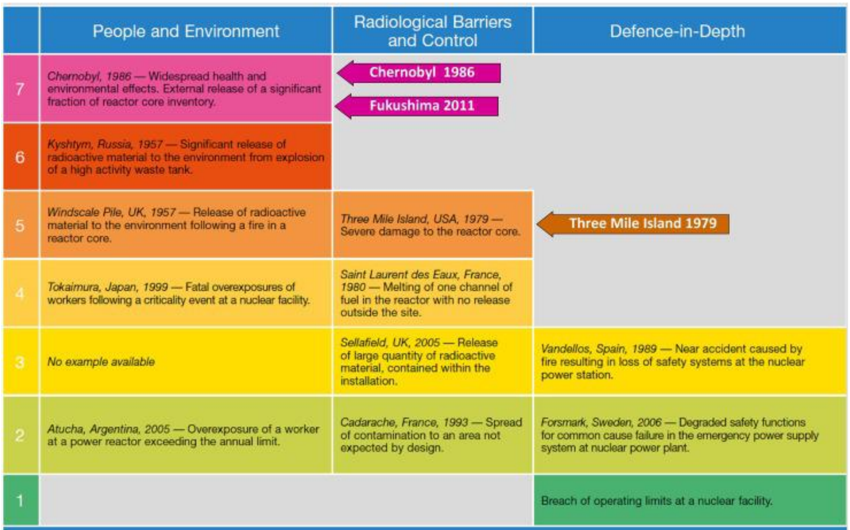

Fig. 2 Examples of events at nuclear facilities, as graded on the International Nuclear Event Scale (INES). Source: IAEA

2. The causes and impacts of three major nuclear accidents

2.1Three Mile Island

The Three Mile Island nuclear power plant is located on an island in the Susquehanna River in Pennsylvania, USA, approximately 15 km from Harrisburg, the state capital. Unit 2 (TMI-2) was a pressurized water reactor with a rated thermal power output of 2700 MW. The reactor was housed within a large dry containment structure made of reinforced concrete see Fig. 3. At the time of the accident on March 28, 1979, TMI-2 was relatively new, having been in operation for only one year.

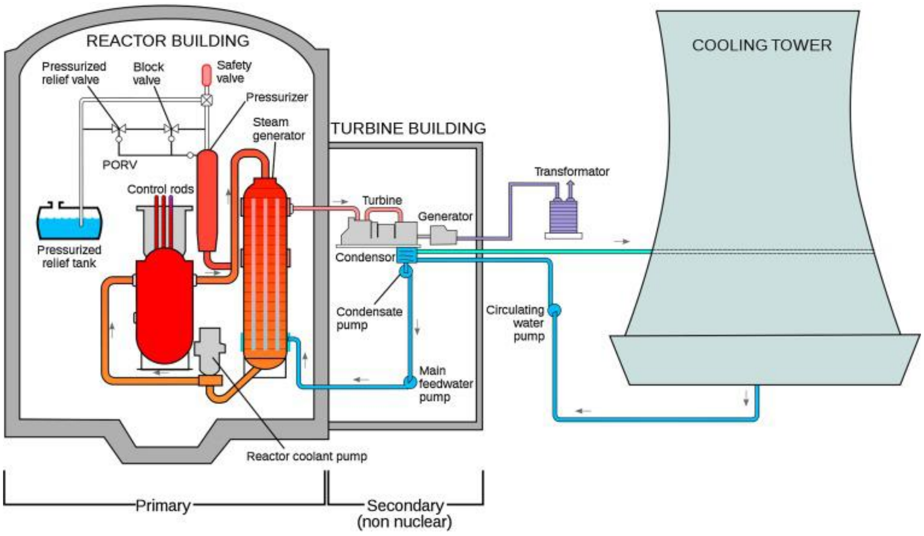

Fig. 3 Schematic of the TMI-2 nuclear power plant. Source: U.S. NRC

The incident began with an operational disturbance that led to a slight pressure increase within the reactor system. Consequently, a relief valve located on top of the pressurizer in Fig. 4opened and became stuck in the open position, resulting in a continuous release of steam and subsequent loss of water from the reactor primary system. Unfortunately, due to inadequate instrumentation, the operators were unaware of the valve malfunction. They interpreted the water level in the pressurizerin fig. 4 as an indication that the core was adequately covered with water, leading them to cease cooling water injection to prevent overfilling the reactor system.

As a consequence of this misunderstanding, the core experienced a condition known as boiling dry, leading to overheating in Fig. 4 and ultimately resulting in a partial core melt. Additionally, a significant amount of hydrogen gas was produced and transported to the containment structure through the malfunctioning relief valve. It wasn't until over two hours later that an operator finally closed the block valve in series with the stuck-open relief valve, initiating the recovery process.

During this time, a hydrogen burn (deflagration) occurred, generating a pressure spike of approximately 0.2 MPa within the containment structure. Fortunately, this pressure spike was well within the design limits of the containment, as it was able to withstand such pressures [12-13].

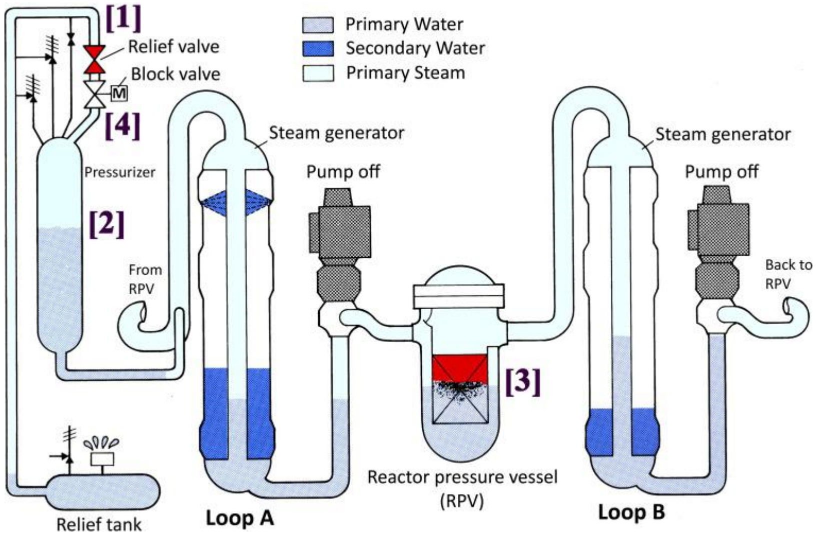

Fig. 4 The status of the TMI-2 reactor system about 2 h after the initiating event.

The condition of the core as it was revealed when the reactor pressure vessel was opened in 1984 is depicted in fig. 5. It was discovered that a minimum of 45% of the core, equivalent to 62 tons, had undergone melting, with 19 tons of this material accumulating in the lower portion of the reactor pressure vessel. Fortunately, cooling measures were reinstated in a timely manner, preventing a complete melt-through of the reactor pressure vessel.

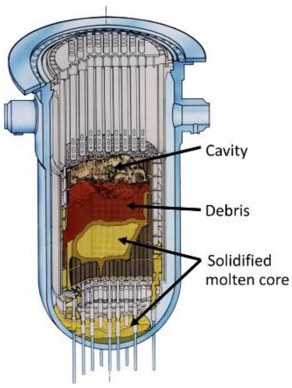

Fig. 5 The end state of the TMI-2 core after the accident. Source: U.S. NRC

Despite significant releases of gaseous and volatile fission products from the damaged core into the reactor containment, only minute quantities of radioactive substances were released into the environment, primarily consisting of noble gases see fig. 6. This limited environmental release was attributed to the preserved integrity of the containment structure[12]. The magnitude of releases to the environment roughly equated to approximately a decade's worth of normal operational releases. The majority of released iodine and cesium ultimately formed various chemical compounds dissolved in the water present in the reactor cooling system and within the containment.

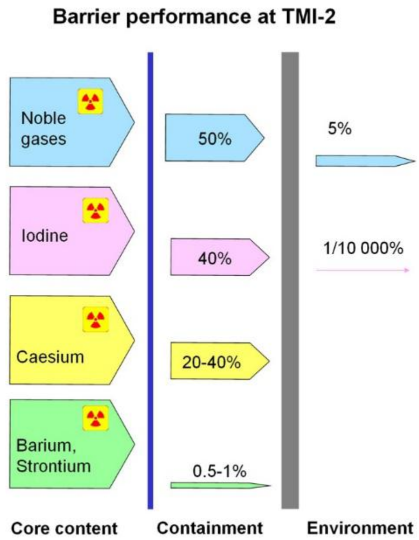

Fig. 6 Releases of radioactive fission products from the TMI-2 core into the containment and to the environment

The Three Mile Island (TMI) nuclear power plant accident, which occurred on March 28, 1979, in Pennsylvania, USA, remains one of the most significant incidents in the history of nuclear energy. This article aims to provide a concise overview of the root causes, radiological impact, socio-economic and socio-political consequences, and the broader impact on the nuclear power sector.

Root Causes:

The accident at TMI-2 was primarily attributed to deficiencies in instrumentation and safety protocols. Key factors included:

1.Inadequate instrumentation: The control room lacked indicators of the actual position of critical components such as the relief valve, hindering operators' ability to respond effectively to anomalies.

2.Ignored safety significance: Probabilistic assessments failed to recognize the safety significance of the relief valve, leading to insufficient training and procedures for operators to address such events.

3.Failure to learn from past incidents: Lessons from similar incidents in other nuclear plants were not incorporated into operator procedures, indicating systemic deficiencies in safety practices across industry stakeholders.

Radiological Impact:

Despite significant releases of gaseous fission products within the reactor containment, only minimal amounts of radioactive substances, mainly noble gases, were released into the environment. The average dose to the surrounding population was estimated to be approximately 0.01 millisievert, with the maximum dose at the site boundary being less than 1 millisievert. Investigations concluded that the release had negligible effects on human health or the environment.

Socio-economic and Socio-political Impact:

The cleanup and removal of damaged fuel at TMI spanned 14 years and cost approximately $1 billion. Total costs of the accident, including reactor loss and other expenses, are estimated to range from $5-10 billion. Additionally, there was a temporary loss of public trust in the industry and authorities due to confusion and lack of communication regarding the reactor's condition.

Precautionary evacuations were recommended for communities within an 8 km radius of the plant.
Impact on the Nuclear Power Sector:

Following the TMI-2 accident, both the U.S. nuclear industry and regulatory authority, the Nuclear Regulatory Commission (NRC), implemented immediate measures to enhance safety practices. The establishment of the Institute of Nuclear Power Operations (INPO) facilitated the exchange of operational experience and peer reviews. However, the incident led to a postponement of new nuclear projects in the U.S., with focus shifting towards improving operation and maintenance practices. International cooperation on nuclear safety was also strengthened, with increased attention to factors influencing human performance, probabilistic safety assessments, and severe accident management techniques.

In conclusion, the TMI-2 accident served as a catalyst for significant improvements in nuclear safety practices globally. While the incident had considerable socio-economic and socio-political repercussions, it also led to enhanced collaboration and advancements in nuclear safety technology and regulation.

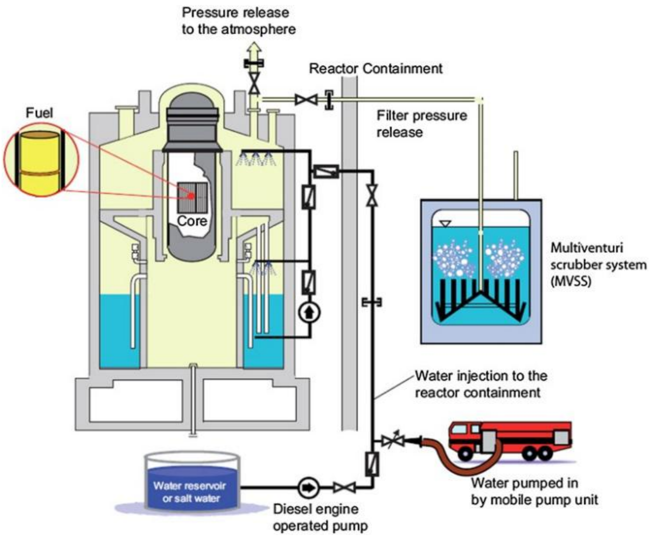

Fig. 7 Severe accident management and release mitigation equipment (filtered venting) installed at Swedish reactors after the TMI-2 accident. Source: Vattenfall AB

Furthermore, the TMI-2 accident significantly influenced energy policy in several countries. In Sweden, for instance, the incident prompted a referendum on nuclear power, culminating in a political decision to maintain the existing 12 reactors while refraining from constructing any new ones. The objective was to gradually phase out nuclear power by the year 2010. This shift in energy policy underscored the heightened public concerns surrounding nuclear safety and sustainability, leading to a reevaluation of the role of nuclear energy in the country's energy mix.

2.2 Chernobyl

The Chernobyl nuclear power plant, located 120 km north of Kiev, the capital of Ukraine, featured Unit 4, which was a graphite-moderated channel-type boiling water reactor. This reactor was of a standard Soviet design known as RBMK, with a rated thermal power output of 3200 MW see fig. 8. The core comprised 1660 fuel channels consisting of zirconium alloy tubes surrounded by graphite. Each channel housed a fuel element cooled by water pumped upward through the channel. Unit 4 commenced operations in 1984.

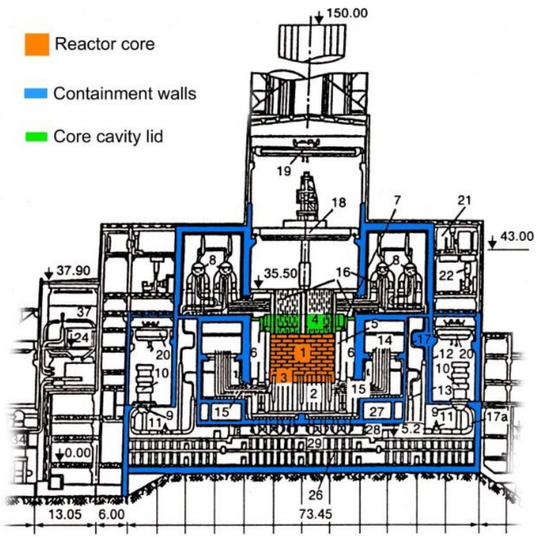

Fig. 8 Cross-section of an RBMK reactor. Source: IAEA/INSAG

During a test program conducted on April 25–26, 1986, operators at the Chernobyl nuclear power plant brought the reactor into an unstable state, violating prescribed operating limits at low power and disabling safety systems. When an operator pressed the "reactor shut-down" button in the early hours of April 26, a powerful power spike was triggered by runaway fission reactions, resulting in the explosive destruction of a significant number of fuel channels. Escaping steam and gases overpressurized the core cavity, lifting and overturning its 1000-ton lid and lifting the control rods out of the core. Another explosion occurred, likely due to the combined effect of control rods disappearing and hydrogen. The reactor suffered complete destruction, with evaporated fuel and fuel fragments ejected high into the air. A fire ignited in the remaining graphite, burning for approximately 10 days see fig. 9, resulting in further radioactive releases[14-15].

Fig. 9 Photos of the scene after the accident occurred.Photo: Unknown Soviet photographer

By the end of November 1986, the damaged reactor at the Chernobyl nuclear power plant had been encased in a temporary shelter, providing weather protection and preventing further release of radionuclides off-site. However, after more than 25 years, the provisional shelter began to show signs of degradation. Consequently, a new safe containment structure is currently under construction, with an expected service life of over 100 years, facilitating the gradual cleanup of

the site.

Releases from the Core and to the Environment:

The explosive nature of the accident dispersed significant portions of the core's radionuclide inventory, particularly gaseous and volatile nuclides, into the environment. Nearly 100% of noble gases, such as Xe-133, were released, along with approximately 60% of the core content of I-131 (equivalent to 1,800,000 TBq) and 30% of Cs-137 (equivalent to 85,000 TBq). A substantial fraction of these releases was lifted to high altitudes due to the explosive characteristics of the accident.

Root Causes:

The Chernobyl accident stemmed from several root causes and deficiencies in safety measures, as outlined by the International Nuclear Safety Advisory Group (INSAG) in 1992:

1.Serious design deficiencies: These included inadequacies in core stability properties, the shutdown system's performance, and the capacity of the core containment to withstand multiple fuel channel ruptures.

2.Inadequate safety analysis and review: Insufficient attention was given to independent safety assessments, leading to gaps in safety protocols.

3.Ineffective exchange of safety information: There was a lack of communication between RBMK plants and between plants and their designers regarding crucial safety concerns.

4.Operator shortcomings: Operators lacked a comprehensive understanding and regard for safety aspects during operational and testing procedures.

5.Weak regulatory regime: The regulatory framework was unable to counter production pressures, contributing to a lax approach to safety.

These deficiencies highlighted a broader lack of safety culture within the political and organizational systems, both at the national and local levels.

Radiological Impact of the Accident:

The significant release of radioactivity resulted in severe ground contamination in the vicinity of the Chernobyl plant. Additionally, substantial amounts of radioactivity were dispersed high into the atmosphere and transported across Europe, leading to significant local ground contamination depending on wind and precipitation patterns. For instance, approximately 4000 TBq of Cs-137 were deposited on Swedish soil.

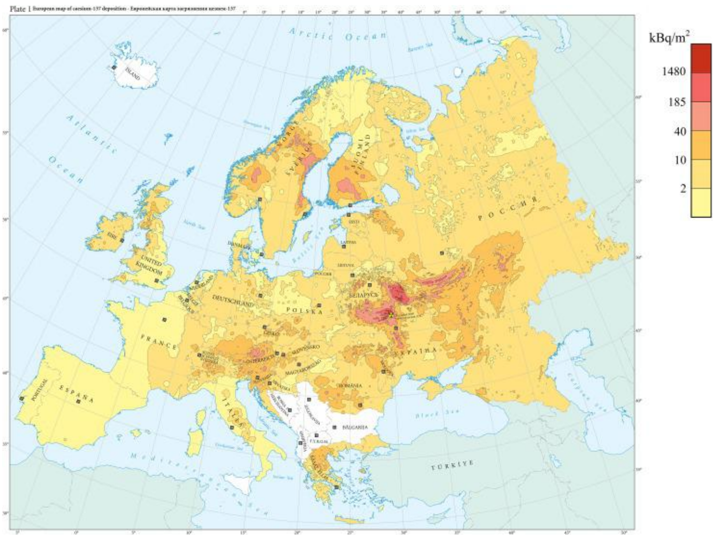

Fig. 10 Cesium deposition on Europe after the Chernobyl accident [16]

Two members of the plant staff were directly killed by the explosion at the Chernobyl nuclear power plant. Additionally, 134 emergency workers were exposed to doses high enough to result in acute radiation syndrome, with 28 of them succumbing to their injuries in 1986. Nineteen more fatalities occurred between 1987 and 2004 due to various causes, some of which may be indirectly linked to radiation exposure.

By 2005, close to 7,000 cases of thyroid cancer had been diagnosed among population groups exposed to radioactive iodine in the months following the accident, with approximately 15 resulting in fatalities. The majority of these thyroid cancers are believed to be attributable to the Chernobyl incident, and this number is expected to rise.

An international expert group estimated that among the 600,000 individuals receiving significant exposures, potentially resulting in radiation-induced cancer mortality rates of a few percent. This could lead to up to about 4,000 fatal cancers, in addition to the roughly 100,000 fatal cancers expected from other causes. Additionally, there are indications of increased incidences of leukemia and cataracts among those with higher radiation doses.

Among the 5 million individuals living in areas with exposures in the 10–20 millisievert range, projected increases in cancer mortality rates are more uncertain but expected to be less than 1%. These increases would be challenging to detect and attribute to radiation exposure due to normal variations in cancer mortality rates.

In Europe, estimates using the linear non-threshold model suggest that up to 25,000 additional cancer cases (other than thyroid) might be attributable to Chernobyl by 2065, compared to over 100 million cases expected from other causes. However, there are considerable uncertainties associated with these estimates, and the use of the linear non-threshold model for risk projections has been questioned by the United Nations Scientific Committee on the Effects of Ionizing Radiation (UNSCEAR).

Regarding socio-economic and socio-political impacts, the total costs over the first 25 years since the Chernobyl accident have been estimated to range from 250,000 to 500,000 million US dollars. More than 300,000 people in the then Soviet Union were evacuated and relocated from their homes in the most contaminated areas, leading to significant stress-related syndromes and mental health issues among the affected population. Additionally, large swathes of agricultural land and forest had to be removed from service due to high levels of contamination, with impacts on timber production and food safety regulations extending across Europe.

The accident also prompted expanded cooperation on radiation safety worldwide, leading to the establishment of new international conventions, revised safety standards, and the creation of organizations such as the World Association of Nuclear Operators (WANO) to implement industry-internal peer reviews on a global scale. The concept of safety culture became central to nuclear safety initiatives, reflecting a broader recognition of the importance of organizational and cultural factors in ensuring nuclear safety.

2.3 Fukushima

The Fukushima Daiichi Nuclear Power Station is situated on the east coast of Japan, approximately 250 km north of Tokyo. The site accommodates six boiling water reactors, all commissioned during the 1970s. Unit 1 had a rated thermal power output of 1380 MW, while units 2 to 5 had a capacity of 2380 MW each. Unit 6, on the other hand, boasted a higher thermal power output of 3290 MW. The general design of units 1 to 5 is depicted in Figure 11, whereas Unit 6 features a newer design.

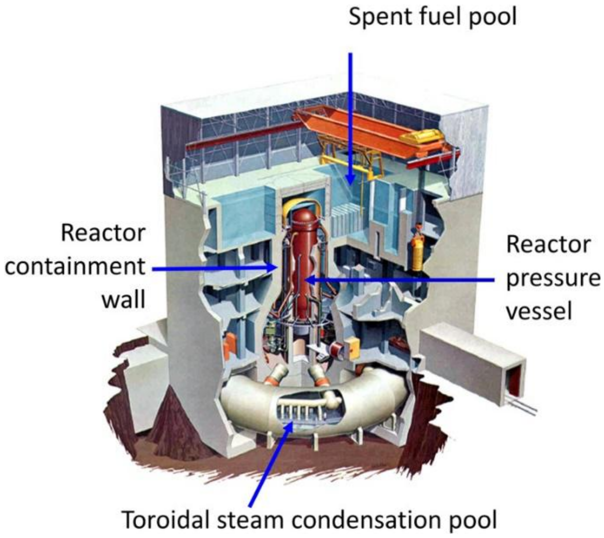

Fig. 11 Schematic of a boiling water reactor (BWR) similar to Fukushima Daiichi unit 1–5.

In a BWR, water pumped through the core is brought to boiling, generating steam that feeds the turbine and its attached generator. The steam condensation pool is designed to condense steam released from a postulated pipe break inside the containment to prevent damage from over-pressure. Source: General Electric

At 14:46 on March 11, 2011, a massive magnitude 9.0 earthquake struck, with its epicenter located in the sea approximately 200 km northwest of the Fukushima Daiichi station. At the time of the earthquake, units 1–3 were operating normally, while units 4–6 were shut down for routine inspections and refueling. As soon as the initial tremors were detected, the power production in units 1–3 was halted, in accordance with safety protocols. The subsequent peak accelerations reached up to 0.56 g in the horizontal direction in some units, slightly exceeding the 0.46 g limit they were designed for. Emergency diesel generators were promptly activated to supply power to crucial cooling and instrumentation systems, compensating for the loss of external power due to damage to transmission lines and switchyards caused by the earthquake. However, it remains uncertain whether the earthquake itself caused any damage to the reactor systems that could have contributed to the severity of the ensuing accident[17].

At 15:41, the tsunami triggered by the earthquake struck the plant, with wave heights reaching heights of about 14 m above sea level, significantly surpassing the design limit of 5.7 m that the reactors were built to withstand see fig. 12. Consequently, the lower levels of the reactor and turbine buildings were flooded with saltwater see fig. 13, resulting in the failure of the emergency diesel generators and substantial damage to power distribution, instrumentation, control equipment, and other systems. This led to the loss of cooling for the reactor cores in units 1–3. Unit 4 had its core unloaded into the spent fuel pool, while units 5–6, located on higher ground than units 1–4, managed to maintain cooling of their reactor cores with the help of one surviving emergency diesel generator.

Fig. 12 The tsunami hits the Fukushima Daiichi Nuclear Power Station on March 11, 2011. Photo: TEPCO

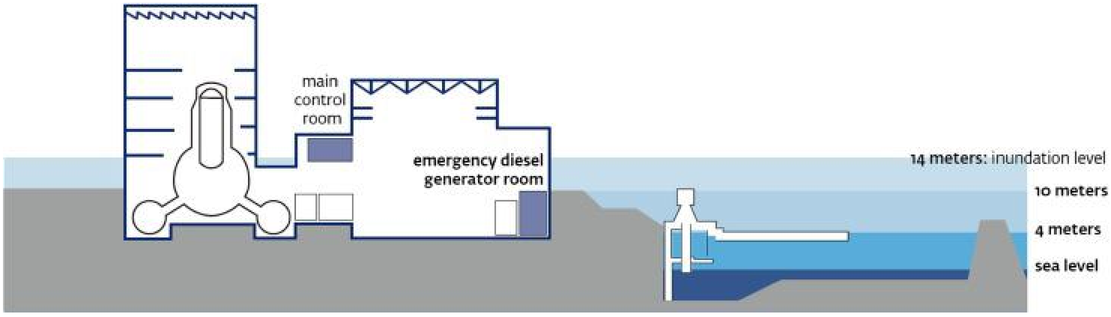

Fig. 13 Cross-section showing the inundation level at Fukushima Daiichi units 1–4 [17]

Operating under challenging conditions, with malfunctioning instrumentation and limited illumination due to power outages, the operators at units 1–4 displayed heroic efforts in attempting to regain control of the situation, albeit without success. Over the following days, the cores in units 1–3 experienced overheating, likely leading to partial or complete meltdown. Molten material from the reactor cores may have breached the bottom of the reactor vessel, with some of it accumulating on the floor of the containment structure see fig. 14. As a result, significant quantities of hydrogen and fission products were released into the containments. The containment structures experienced leaks due to overpressure and other potential factors. The release of hydrogen resulted in violent explosions that demolished the upper sections of the reactor buildings in units 1, 3, and 4 see fig. 15. Substantial amounts of radioactive fission products escaped into the environment.

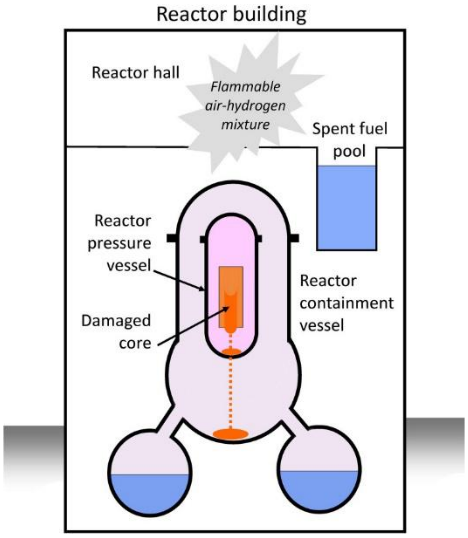

Fig. 14 Simplified schematic of reactor status after core overheating and partial meltdown, based on theoretical calculations [18]

Fig. 15 Damage to the reactor buildings of units 3 and 4 caused by hydrogen explosions on March 14–15 (NAIIC 2012). Photo: Air Photo Services, Japan

It was only by the end of 2011 that the situation began to stabilize across all units, with recirculation cooling established for the damaged cores in units 1–3 see fig. 16, and temperatures within the reactor pressure vessels and containments were well below 100°C. Additionally, stable cooling of the spent fuel pools in all units had been achieved. Clean-up operations were initiated, including the removal of spent fuel from the pool in unit 4. However, the daunting task of complete site cleanup is underway, with estimates suggesting it will take between 30 to 50 years to complete, largely due to the challenging working conditions within the damaged reactors.

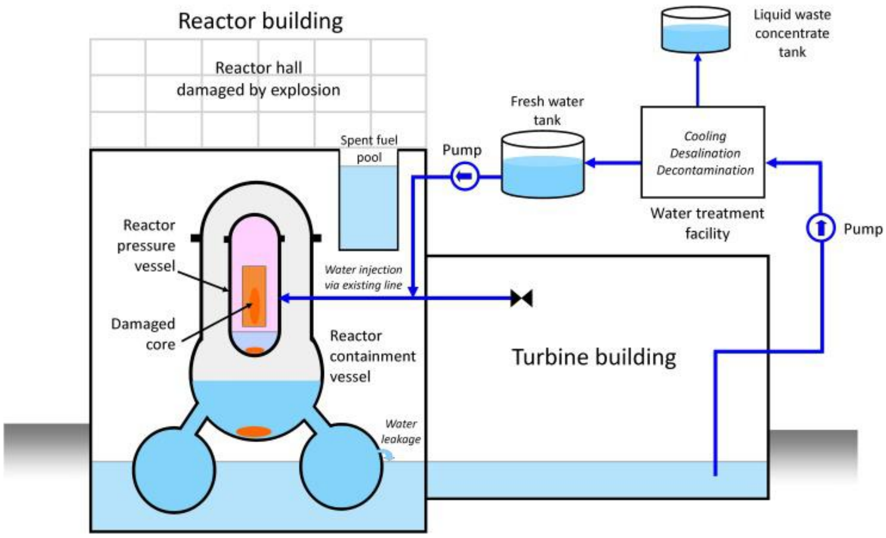

Fig. 16 Simplified schematic illustrating how the damaged cores of units 1–3 are presently cooled

Releases from the Core and to the Environment:

Similar to the Three Mile Island incident, a significant portion of the fission products were released into the reactor pressure vessels and the containments in units 1–3. Through leaks and other mechanisms, approximately 150,000 TBq of I-131 and around 12,000 TBq of Cs-137 escaped into the atmosphere. According to Japanese estimates, around 4,000 TBq of Cs-137 leaked into the sea in the first months after the accident, although substantially higher amounts have been estimated by French experts[19].

Root Causes:

While the immediate cause of the accident was the damage to the plant and the power grid caused by the combined effect of the earthquake and subsequent tsunami, the inadequate protection against the tsunami was a critical factor. Although Japanese reactors are designed to withstand earthquakes as strong as the one that occurred on March 11, 2011, historical records see fig. 17 indicate that tsunami waves exceeding heights of 10–20 m have occurred several times in the past few hundred years. Therefore, such waves should have been included in the plant's design basis according to international safety standards such as those published by the IAEA.

Moreover, training, procedures, and equipment for managing severe accidents were far from what is considered good international practices after incidents like TMI and Chernobyl. Both the plant owner (TEPCO) and the regulatory authority (NISA) were aware of this situation but failed to take appropriate actions, delaying decisions on safety upgrades for various reasons.

The Fukushima Nuclear Accident Independent Investigation Commission appointed by the National Diet of Japan (the Japanese Parliament) strongly criticized the multitude of errors and willful negligence that left the Fukushima plant unprepared for the events of March 11, 2011. The commission concluded that the disaster was "Made in Japan," with fundamental causes rooted in the ingrained conventions of Japanese culture, including reflexive obedience, reluctance to question authority, devotion to 'sticking with the program,' groupism, and insularity [20].

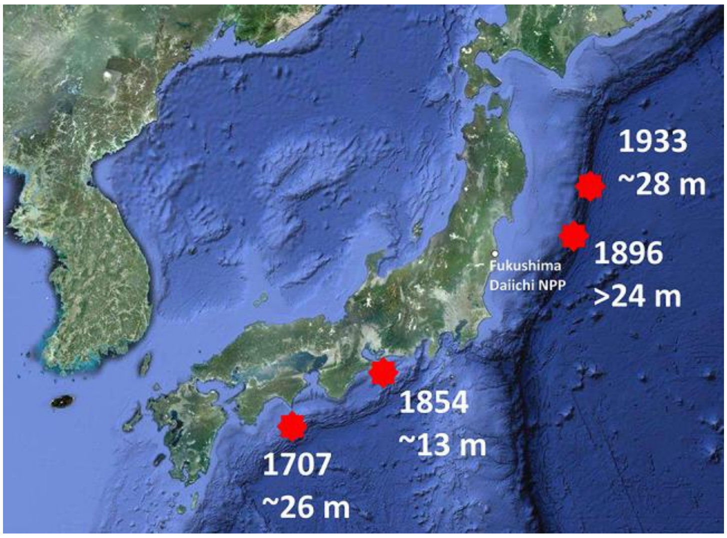

Fig. 17 Historical records of tsunami waves exceeding a height of 10–20 m[18]. Map: Google Earth

Radiological impact of the accident, the airborne releases of radioactivity, compounded by rainy weather, led to significant ground contamination, particularly in a plume extending approximately 40 km to the northwest of the Fukushima Daiichi plant (refer to the map in Fig. 18). Estimates suggest that an area as large as 1800 km2 of land has contamination levels resulting in potentially cumulative radiation doses of 5 millisieverts or higher per year [20].

Surveillance and control of radioactivity in various food products are expected to remain in place for many years to come to ensure the safety of the population.

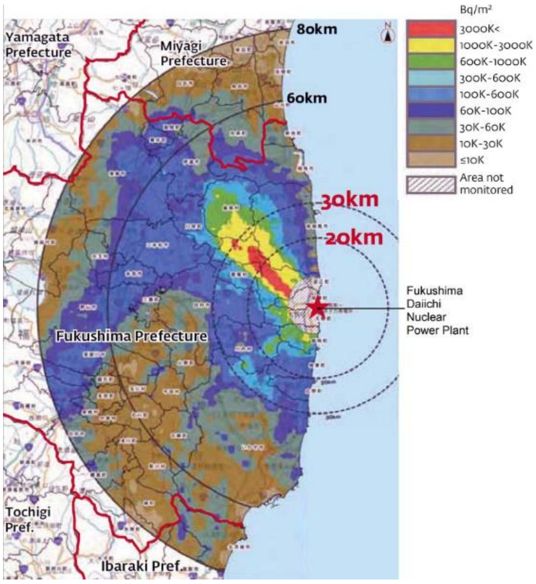

Fig. 18 Map of accumulated deposits of Cesium-137 as of July 2, 2011 [20]

Contrary to Chernobyl, no cases of acute radiation syndrome have been reported thus far. However, the risk of accidental occupational exposure during clean-up operations on-site remains. During the course of managing the accident, 167 workers were exposed to more than 100 millisieverts, with many more expected to receive doses up to 100 millisieverts during ongoing clean-up efforts.

An estimate of the cumulative external exposure over the first 4 months following the accident for approximately 14,000 residents (excluding plant workers) from three towns and villages with

relatively high radiation doses shows that 0.7% of the residents were exposed to 10 millisieverts or more, 42% to less than 10 millisieverts but more than 1 millisievert, and 57% to 1 millisievert or less [20]. Although detailed initial exposure data are lacking, it seems reasonable to assume that residents from less contaminated areas have been exposed to similar dose bands [21]. Future epidemiological studies over several decades are needed to determine if any increases in cancer incidence attributable to the accident can be detected. Given the numbers exposed and the doses received, statistically significant increases are unlikely to be expected, except perhaps for thyroid cancers in children from the most exposed areas.

Similar to Chernobyl, the most severe health impact appears to be stress-induced psychosomatic syndromes related to uncertainties about individual doses received, the disruption of family lives, and societal fabrics resulting from evacuation and continuing uncertainty about the possibility of returning to the contaminated areas [20]. While the root causes of the stress will persist for many years, efforts to empower residents could alleviate the situation to some extent. For example, residents returning to less contaminated areas could be equipped with knowledge and tools to evaluate and control their exposure themselves. Such tools would include easily understood information on the health risks associated with small to moderate additional doses, provision of simple radiation monitoring instruments and methods, and tools for reducing contamination and exposure. Such approaches are now being promoted in Japan[22].

Socio-economic and Socio-political Impact Approximately 150,000 people have been evacuated from the contaminated zones, mainly within a radius of 20 km from the plant. Evacuation became somewhat chaotic as evacuation zones were expanded from a 3-km radius to a 20-km radius, all within a single day. Evacuation of hospitals faced difficulties, and it has been estimated that approximately 60 patients died from complications related to the evacuation. Some limited returns have begun, but residents in the most contaminated areas will face challenges in returning for a long time [20].

Before the accident, 54 reactors supplied about 30% of the electricity in Japan. Several reactors on the east coast were shut down automatically due to the earthquake, with others successively shut down as they entered their annual refueling and maintenance outages. None were permitted to restart pending safety reviews and local political approval. By the beginning of May 2012, all Japanese power reactors were shut down, and by November 2012, only two reactors had been allowed to restart. The restart of more reactors is expected to take time, partly due to the need for technical safety improvements and partly due to a loss of trust in the nuclear industry and government authorities, delaying local political approval.

The loss of nuclear electricity production has been partially offset by increased production from fossil-fueled plants, but several electricity-saving measures have also been necessary. Imports of fossil fuels have increased to the extent of significantly affecting Japan's trade balance, and CO_2 emissions have risen. A thorough review of Japan’s long-term energy policy is underway. No political decisions have yet been made by the new government formed after the parliamentary elections in December 2012. A reduction in dependence on nuclear power is expected compared to the plans envisaged before March 2011. A total phase-out of nuclear power is among the options being considered.

The total costs of the accident over a 50-year perspective are difficult to predict, but different cost estimates presently range from 100,000 to 500,000 million US dollars, corresponding to about 2–10% of Japan’s annual gross domestic product. The Japanese government has been compelled

to effectively nationalize the utility (TEPCO) that owns the Fukushima plant to cover the costs of the accident and continue providing electricity to the Tokyo region.

International Impact Internationally, the Fukushima accident has prompted substantial efforts aimed at reassessing and strengthening the safety of nuclear power plants. The EU and other countries have conducted "stress tests"[23], which include reassessing plant vulnerabilities to extreme and unlikely events affecting multiple reactors at the same site, enhancing capabilities to cool the core and spent fuel pools during such events, and strengthening severe accident management capabilities at the plants, including equipment, procedures, and training.

For example, many more countries are now considering implementing similar types of severe accident management and release mitigation systems that Sweden and some other countries installed in the 1980s see fig. 7. Had they been in place at the Fukushima reactors, it is likely that both on-site and off-site radiological consequences would have been substantially reduced, even if core melts probably could not have been avoided.

Finally, the Fukushima accident has had a profound impact on energy policy in some countries, such as Belgium, Germany, and Switzerland, which are planning to phase out nuclear power. On the other hand, construction of new reactors continues in many other countries, albeit with some delays due to safety reassessments of the type described above. By the end of October 2012, 64 new reactors were under construction, with the majority in China, Russia, India, and the Republic of Korea (IAEA PRIS 2012).

3. Conclusions

The outcomes of the accidents at TMI-2, Chernobyl, and Fukushima underscore that severe reactor accidents are not unique in terms of the number of directly attributable fatalities resulting from energy production-related accidents. For instance, the Banqiao dam collapse in Hunan, China in 1975 and the 1963 landslide into the Vaiont dam in Italy each caused many thousand fatalities. Moreover, it has been estimated that with proper off-site emergency response programs, the contribution to individual fatality risk (both early and late radiation-induced fatalities) from severe reactor accidents is small compared to other individual health risks, even with releases of Cs-137 in the range of several thousand TBq (U.S. NRC 2012). Thus far, assessments of the radiological health consequences of Fukushima do not seem to contradict these estimates.

However, severe reactor accidents involving radioactive releases of several thousand TBq or more of radionuclides like Cs-137 may lead to unique socio-economic and socio-political consequences due to large-scale and long-lived ground contamination, resulting in associated human and monetary costs.

Hence, reactor safety objectives should not only aim to limit contributions to individual health risks but also to mitigate socio-economic impacts. Therefore, releases of Cs-137 should be capped at around a hundred TBq at most, even in the event of a core meltdown. Additionally, achieving a stable end state in the reactor with the damaged core cooled and covered with water in a containment with preserved integrity and at atmospheric pressure is crucial. Such an end state would not only substantially reduce the risks of radioactive releases but also, as observed in TMI, facilitate long-term clean-up activities and associated cost reductions. These severe accident management capabilities are attainable in new reactor designs and can also be implemented in many existing reactors through appropriate retrofitting measures. This implies that the likelihood of a large-scale release akin to Chernobyl and Fukushima could be significantly diminished, even

if complete elimination is not feasible.

Lastly, the significance of upholding high global standards of safety management and safety culture cannot be overstated. All three severe accidents discussed above had their origins in system deficiencies indicative of inadequate safety management and culture within both the nuclear industry and government authorities. Without effective and continual global scrutiny for such deficiencies—by industry, governments, international organizations—and subsequent corrective actions, the likelihood of a future severe accident occurring somewhere in the world cannot be expected to see a dramatic reduction compared to historical experiences thus far.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Duanman Xiong,Yuxin Fang,Jingxu Wu,Junwen Wu,Jiaqi Zhang,Haoqin Yang and Guoyu Chen. The first draft of the manuscript was written by Duanman Xiong, Jingxu Wu and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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